ERDC/CHL CHETN-IV-74
September 2009

US Army Corps of Engineers®

Concepts for Functional Restoration of Barrier Islands

by Julie Dean Rosati

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) presents guidance for functional restoration of barrier islands. The concept of functional restoration is introduced here as an engineering and ecological design such that a barrier island can perform as a wave attenuator, storm surge buffer, and ocean boundary for an estuary, bay, and mainland over the defined project lifetime. Ecological design is required as part of the restoration to minimize initial nourishment losses and to ensure that environmental goals are met. Functional restoration allows for the possibility that a restored island could migrate alongshore and cross-shore, and possibly overwash to some extent as long as it continued reducing the risk of damage to the estuary, bay, and mainland. This CHETN reviews existing knowledge on the benefits of barrier islands and presents guidance for functional restoration.

INTRODUCTION: The U.S. Army Corps of Engineers can be involved in the restoration of barrier islands in two mission areas: storm damage reduction and environmental restoration. Barrier islands have been called the “first line of defense” in reducing storm wave and surge damage to mainland coastlines (Stone and McBride 1998, Grzegorzewski et al. 2009). Numerical simulations have quantified some of the storm damage reduction benefits of barrier islands for site-specific cases, as discussed below.

Stone et al. (2003) simulated waves and surge for a Category 3 hurricane for the barrier islands surrounding Terrebonne Bay, LA. The simulations were conducted for barrier island positions and marsh coverage in 1950 and 1990, and those forecasted for 2020. Between 1950 and 1990, the subaerial land footprint in the Terrebonne Bay area (barrier islands and wetlands) decreased by 24 percent (Stone and McBride 1998, Barrier Island Feasibility Study 1999), and this trend was extrapolated to develop the 2020 topographic condition. For a Category 3 hurricane, Stone et al. (2003) calculated a typical increase in the total water level (surge, wave height, and wave setup) along the barrier islands and marshes from 1950 to 1990 of 8-10 ft, and an increase of 10-12 ft from 1990 to 2020 (Figure 1). Maximum differences of 32 ft (1950 to 1990) and 45 ft (1990 to 2020) occurred where islands or landmass became water between the two time periods, near East Timbalier Island and Fourchon. Calculations of the potential change in total Category 3 hurricane water levels near a barrier island and within the bay behind it indicate how reduction of the island footprint increases the severity of the storm on the mainland coast.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **SEP 2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Concepts for Functional Restoration of Barrier Islands**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **U.S. Army Engineer Research and Development Center,Environmental Laboratory,3909 Halls Ferry Road,Vicksburg,MS,39180-6199**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

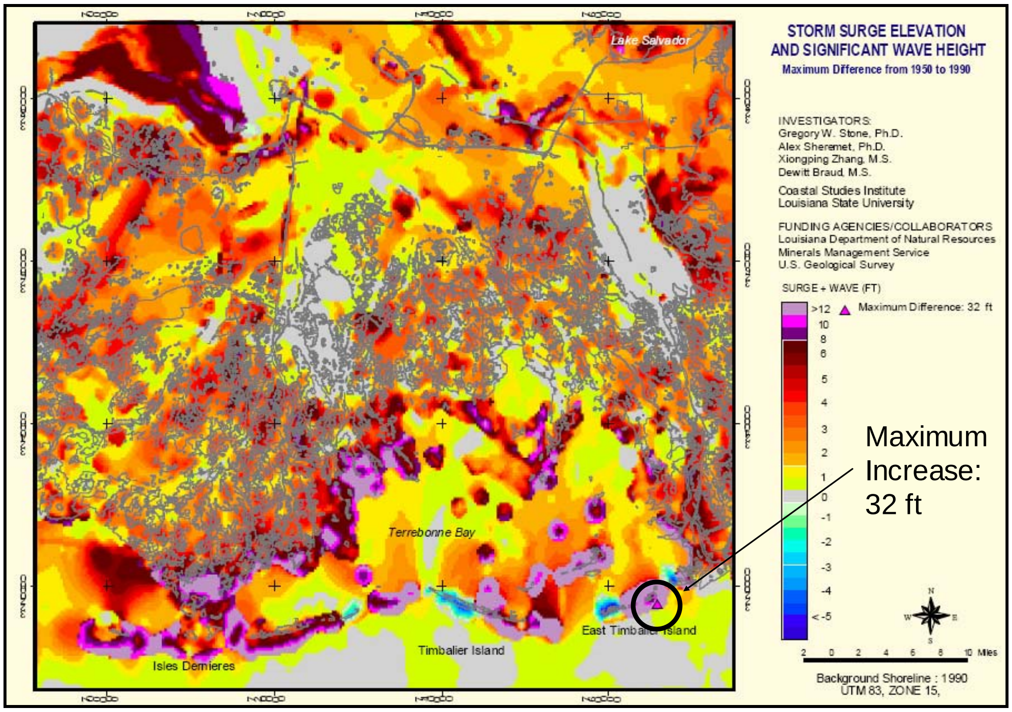
13. SUPPLEMENTARY NOTES

14. ABSTRACT

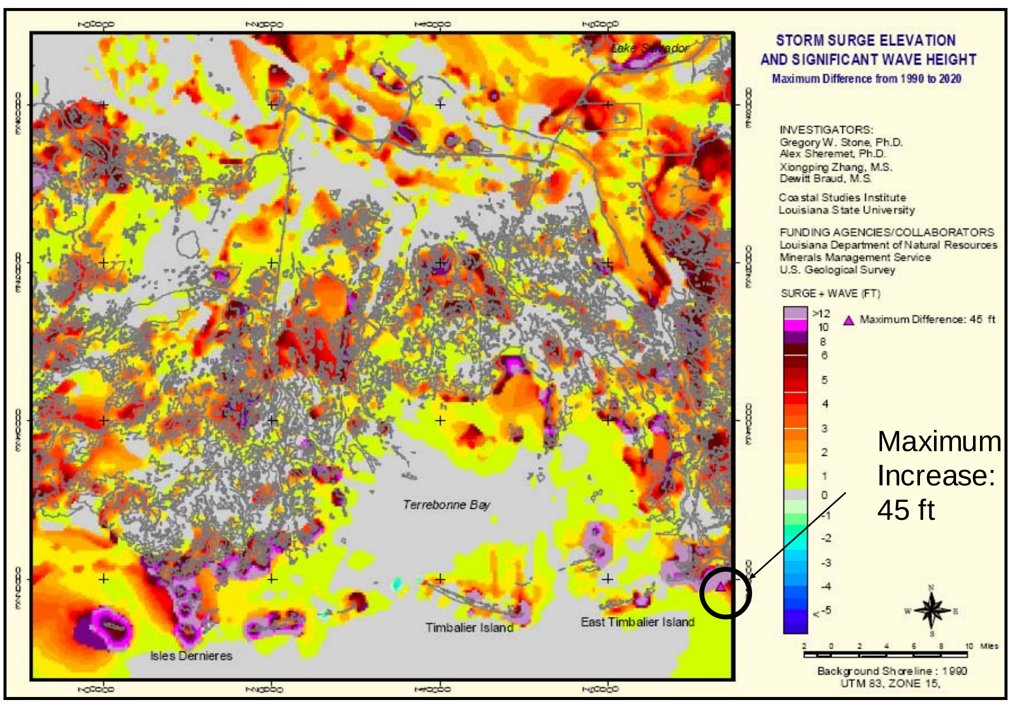
15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**14**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18



a. Landscape in 1950 vs.1990



b. Landscape in 1990 vs. projected in 2020

Figure 1. Numerical modeling of a Category 3 Hurricane for Terrebonne Bay, LA showing the difference between total water level (storm surge, significant wave height, and wave setup) as calculated with subaerial land footprint in (a) 1950 and 1990, and (b) between 1990 and projected position in 2020 (from Stone et al. 2003).

Grzegorzewski et al. (2009) conducted coupled numerical wave and circulation modeling for 15 hypothetical hurricanes along the Mississippi and Louisiana coasts, for barrier islands in degraded (entirely subaqueous), existing, and restored conditions. As compared to the existing condition, restoration of the barrier islands (to +6 ft in Louisiana and +12 ft in Mississippi relative to NAVD88 2004.65) reduced maximum significant wave height in the lee of the islands as much as 90 percent, and decreased peak storm surge elevation by 12 percent. Restoration of the islands also delayed the peak of the surge by 2 hr as calculated landward of the Chandeleur Islands, Louisiana. Calculations with the islands in a degraded condition showed a substantial increase in maximum significant wave height (a maximum nearly 5 times greater than the existing condition), increased the peak surge by 12 percent, and advanced the timing of the peak surge by several hours, as computed landward of the Chandeleur Islands. Wamsley et al. (2009) conducted similar simulations with coupled wave and circulation models for the Chandeleur Islands for two hurricanes that approximate Hurricanes Hilda (landfall in south-central Louisiana in 1964) and Katrina (landfall east of New Orleans in 2005). These simulations indicated that degradation of the Chandeleur Islands increased the peak storm surge slightly (less than 1.6 ft) at the hurricane protection system in New Orleans and increased wave heights in Breton Sound (to the lee of the islands) by 3.3 to 13 ft.

Barrier islands are also habitat for permanent and migrant bird populations (Moore et al. 1990), and foster a quiescent habitat in protected estuaries and bays. Species such as shrimp require tidal circulation and gradient in salinity within estuaries as a part of their juvenile growth cycle, which is promoted by the presence of barrier islands and freshwater flow into estuaries (Texas Parks and Wildlife 2002, Reyes et al. 2002). Estuaries, particularly those on deltaic coasts, represent the most productive ecosystems in the world yet they are the most threatened by anthropogenic activities (Edgar et al. 2000). Because of populated areas near the coast, infrastructure, and hardening of mainland shorelines, estuaries are limited in potential expansion with relative sea level rise (so-called “coastal squeeze,” French 2006).

Approximately 12 percent of the world’s open-ocean coast is fronted by barrier islands, and 28 percent of these islands occur in deltaic systems (Pilkey and Fraser 2003). The benefits and functioning of barrier islands, especially those in deltaic settings, are threatened by reduced sources of sand, relative sea level rise, and anthropogenic activities. Intervention to restore barrier islands through placement of beach-quality sand from an external source has been conducted since the 1920s (Farley 1923, Marine Board 1995) and continues to be considered in increasingly large-scale, regional applications (van Heerden and DeRouen 1997). This CHETN aims to discuss functional restoration of barrier islands in a more complete and dynamic way than traditional beach nourishment for storm damage protection.

FUNCTIONAL RESTORATION:

Functional restoration is defined herein as an engineering and ecological design such that a barrier island can perform as a wave attenuator, storm surge buffer, and ocean boundary for an estuary, bay, and mainland over the defined project lifetime. The restoration is intended to be dynamically stable in that the barrier island is designed to allow morphologic evolution through time via migration and overwash, as long as the storm protection and ecological design goals are achieved. Ecological design is required as part of the restoration to minimize initial nourishment losses and to ensure that environmental goals are met.

Campbell et al. (2005) discussed two approaches for restoration of barrier islands in coastal Louisiana. The first is a "stable design," in which the project is planned such that the island is maintained in a geographic location by eliminating frequent overwash and breaching. The second is "retreat design," which allows the island to migrate, but maintains a constant island area. The difference in design for these two types of restoration enters into the dune elevation and the amount of fine sediment (e.g., clay and silt) that is lost offshore over the project life. The retreat design of Campbell et al. (2005) is closer to the concept of functional restoration, although the requirement for constant island area is not necessarily a component of functional restoration.

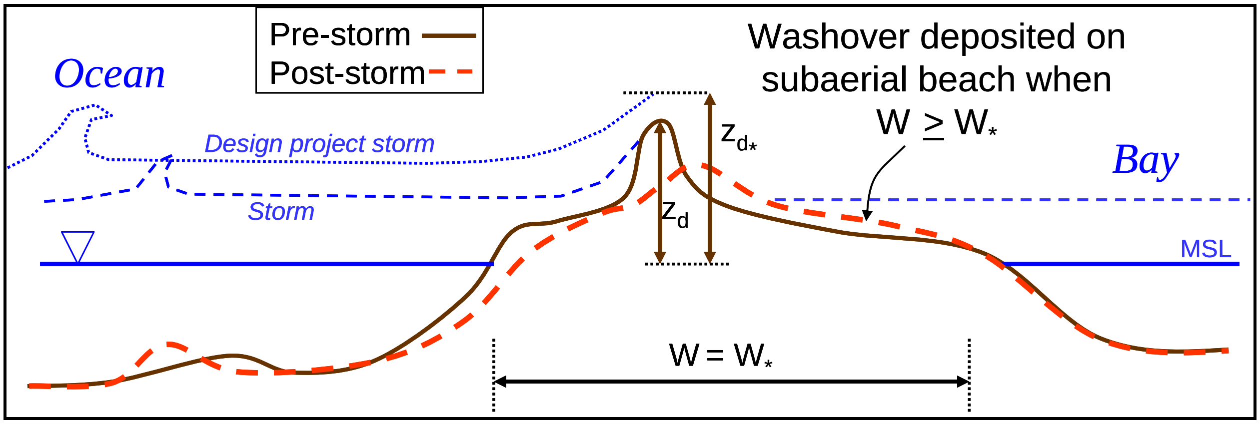
In summary, the design goal for functional restoration is to create an island that will be dynamically stable, allowing natural evolution while providing protection for the estuary, bay, and/or mainland over the defined project duration. The design challenges are to determine the minimum or so-called "critical" dimensions (dune elevation, island cross-shore width, and alongshore length) and associated ecological design, such that the wave and surge protection and environmental benefits are realized.

CRITICAL ISLAND DIMENSIONS:

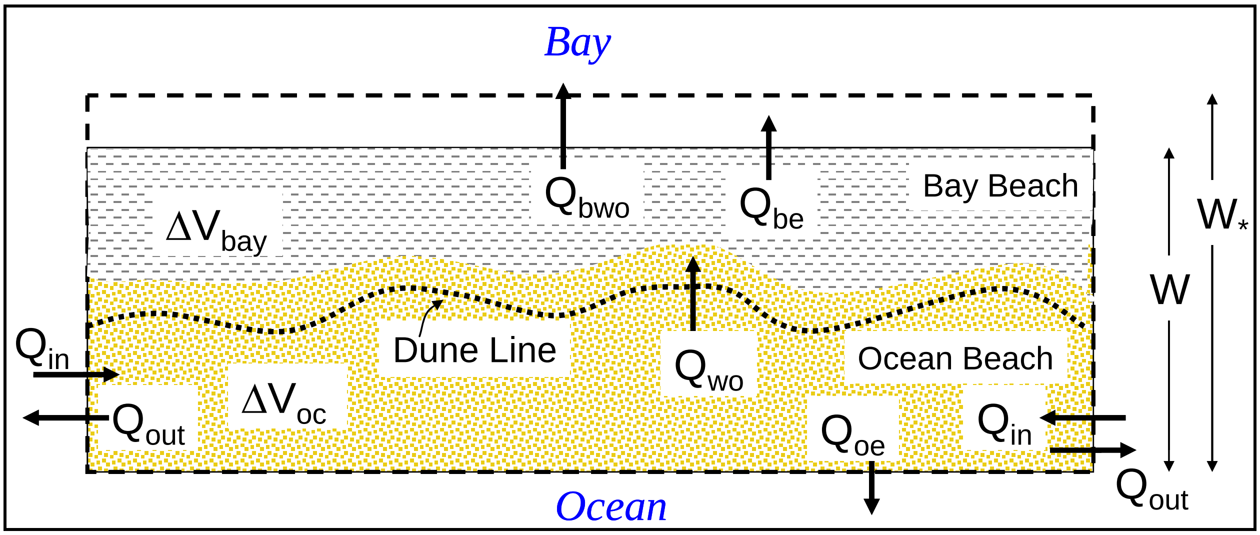
The word "critical" has been applied to describe the minimum cross-shore barrier island dimensions (width and elevation) required to maintain morphologic form and increase the potential for island recovery after a storm. For example, an island with sub-critical width is more likely to breach and develop a permanent inlet, which could result in island break up and degradation. Critical width has been discussed with reference to barrier islands, overwash, and washover deposits since the 1970s (e.g., Leatherman 1976, 1979; Jiménez and Sánchez-Arcilla 2004; Rosati and Stone 2007). For the present discussion, critical barrier width is defined as the smallest cross-shore dimension that minimizes net loss of sediment from the barrier island over the defined project lifetime. The magnitude of critical width is related to sources and sinks of sand in the system, such as the volume stored in the dunes and the net longshore and cross-shore sand transport, as well as the island elevation. To illustrate the definition and introduce terminology, Figure 2 shows a schematic barrier island and sediment transport pathways.

If the barrier width, W, equals or exceeds the critical value, W_*, transport of washover sediment from the ocean beach, Q_{wo}, is deposited entirely on the bay beach, and residual loss of this washover into the bay, Q_{bwo}, equals zero. For barrier widths less than the critical value, $Q_{bwo} > 0$.

Leatherman (1976, 1979) investigated overwash and washover along the northern end of Assateague Island, MD and found that overwash processes were effective in migration of the barrier "…only where the barrier width is less than a critical value (122 to 213 m)." The island did not narrow below these values because overwash was effective at transporting sediment to the bayshore, thereby keeping pace with the rate of ocean shoreline recession (Figure 3). Sections of the island with greater widths experienced washover deposits that did not reach the bayshore, and the island narrowed by ocean shoreline recession until it reached the critical width. The only process that widened the barrier beyond the critical width was breaching, formation of a partially subaerial flood shoal, and subsequent inlet closure (Leatherman 1976).



a. Cross-section for W=W*



b. Planview, W < W*

<u>Legend</u>

Q_{in} = longshore transport rate into barrier system

Q_{out} = longshore transport rate out of barrier system

ΔV_{oc} = volume change rate on ocean beach

ΔV_{bay} = volume change rate on bay beach

W = barrier width

W_* = critical barrier width

Q_{oe} = rate transported offshore

Q_{be} = rate transported into bay

Q_{wo} = washover rate from ocean beach

Q_{bwo} = washover rate lost into bay

z_d = dune elevation

z_{d*} = critical dune elevation

Figure 2. Definition of terminology

Figure 3. Assateague Island overwash from Northeaster, February 1998 (USGS, 2008)

Eitner (1996) discussed potential response of the East Frisian barrier islands due to a 1-m rise in sea level occurring over approximately 170 years. Although critical width is not discussed, the most likely future outcome proposed is one in which the barrier islands maintain width while increasing in height and migrating landward. This stability of barrier cross-section implies that a critical width is maintained over the long term. Jiménez and Sánchez-Arcilla (2004) applied the concept of critical width in a decadal-scale barrier evolution model to determine when overwash processes would contribute to bayshore accretion. They developed the model for the Ebro Delta, Spain, and estimated the critical width of the barrier spit as 225 m.

Critical width can be estimated through a sediment budget approach (Figure 1). Applying the requirement that Q_{wo} remain on the subaerial beach at critical width (i.e., $Q_{bwo} = 0$ if $W = W_*$), and assuming that transport of the washover sediment into the bay, Q_{bwo}, is linearly related to the critical width, then:

$$W_* = W\left(\frac{Q_{wo}}{Q_{wo} - Q_{bwo}}\right), \quad \text{or}$$
$$W_* = W\left(\frac{Q_{in} - Q_{out} - Q_{oe} - \Delta V_{oc}}{Q_{be} + \Delta V_{bay}}\right) \tag{1}$$

Stone et al. (2004) compiled total volumes for four barrier components at Santa Rosa Island, FL (Gulf, Berm, Dune, Bay Beach, and Bay Platform) over a 6-year period, which can be used in Equation 1 to determine the critical width. Considering volumetric change from February 1996 to 2002, a sediment budget can be formulated as shown in Figure 2. In formulating this budget, it was assumed that all volumetric change was by cross-shore transport, and the gradient in long-shore transport was zero. Applying Equation 1 with a barrier width W = 220 m, $Q_{in} - Q_{out}$ = 0 cu m/yr, Q_{oe} = 12.8 cu m/yr, ΔV_{oc} = -40.8 cu m/yr, Q_{be} = 0 cu m/yr, and ΔV_{bay} = 24.5 cu m/yr, the critical width can be estimated as, $W_* = 220\left(\dfrac{0-12.8-(-40.8)}{0+24.5}\right) = 250\,\text{m}$.

Together with beach width, dune crest elevation and berm width are primary design parameters for storm damage reduction projects (Gravens et al. 2006). The Coastal Engineering Manual (CEM) (Gravens et al. 2006) recommends that the dune crest (z_d in Figure 2) should be at an elevation equal to the limit of wave runup for the defined project storm (shown as z_{d*} in Figure 2), and the berm seaward of the dune should be of sufficient width to withstand erosion associated with the design storm.

Sallenger (2000) proposed a four-level Storm Impact Scale that incorporates elevation of the barrier island relative to wave runup during storms in determining morphologic response (Figure 4).

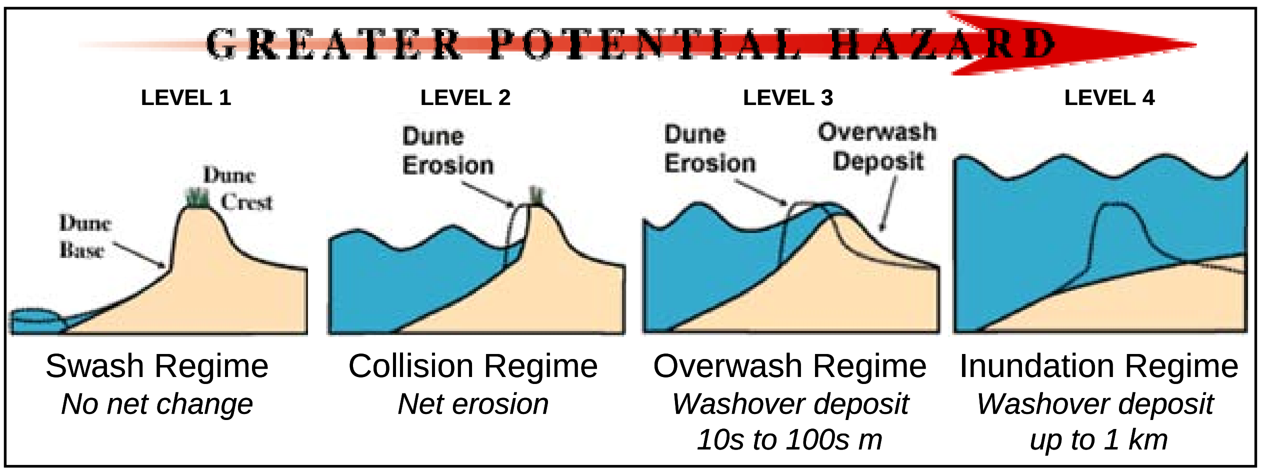


Figure 4. Storm Impact Scale from Sallenger (2000) (adapted from USGS 2008)

The lowest level of impact occurs with Level 1, "Swash Regime," in which wave runup erodes the beach foreshore. Over periods of weeks to months, the sand returns to the beach. "Collision Regime," Level 2, occurs when wave runup erodes the base of the dune and is transported off-shore, resulting in a net loss of sand to the dune system. Level 3 is "Overwash Regime" and occurs as wave runup exceeds the highest elevation of the island. The washover sand is trans-ported landward for 10s to 100s of meters, contributing to net migration of the island landwards. The most severe impact is Level 4, "Inundation Regime," and occurs when the highest elevation on the island is subaqueous during the storm. During Inundation Regime, sand can be transported landwards up to 1 km. The Storm Impact Scale implicitly captures the significance of barrier island width as well as elevation, because an island wider than the washover deposit (10s to 100s

of meters for Level 3, and up to 1 km for Level 4) will be more likely to retain the sand deposit on the subaerial island. And an island with elevation greater than the storm runup will be able to withstand overwash until the dune is eroded, which incorporates the width of the dune into the Impact Scale.

Therefore, critical width and critical elevation are not independent variables. Functional restoration of barrier islands would be best considered within the context of a critical cross-sectional area. Large-scale restoration involves reconstruction of the island to specified height, width, length, and spacing (for multiple islands) using sediment derived from an external source. The following sections discuss other design considerations.

REGIONAL SETTING AND GEOLOGIC CONSTRAINTS:

Regional setting and geologic constraints include: (1) the net source or sink of littoral sediment to the barrier island; (2) the potential loss of sand from the island to inlet channels and shoals; (3) considering bayshore processes in design; (4) native sediment size, distribution, and type; (5) availability of sediment for restoration; (6) relative sea level trends in the region; and (7) the potential for compression of the substrate with the added weight of the restoration sediment. Items (1) and (2) are addressed in terms of Q_{in} and Q_{out}, shown in Figure 2, and are not discussed further other than to emphasize that the local and regional, short- and long-term net sources and sinks of littoral sediment must be included in the island budget and design. Items (3) through (7) are discussed below.

For barrier islands protecting large bays, wind-generated waves on the bay can erode the bay shoreline. For these types of settings, islands constructed in the bay can provide wave protection on the bayshore of the island and additional ecological habitat in the region (Figure 5). These islands can be created with dredged sediment if they can be contained (a temporary dike may be required during the construction and dewatering process) and not interfere with navigation.

The majority of barrier islands are composed of sand, although some barrier islands include a finer silt, clay, mud, and organic marsh on the back-barrier, and the sand beach may overlay a core of finer sediment and organics. Traditionally, sand is the preferred sediment for beach restoration because of its compatibility with the native sand and general stability as compared to finer sediment. However, in many locations sand resources for restoration are becoming scarce or too expensive. For these systems, a mixed sediment restoration may be considered.

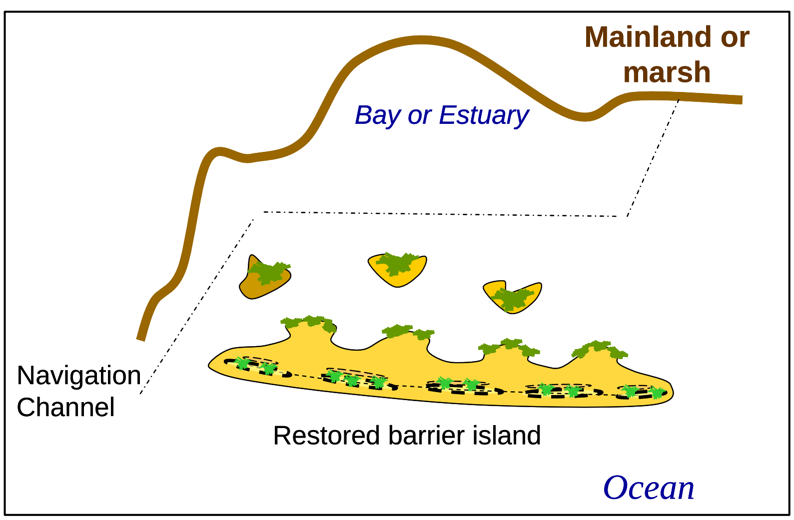


Figure 5. Regional design for artificial islands in the bay to provide wave protection and additional habitat

King et al. (2009) compared two dunes in Jefferson County, TX, one constructed with a clay core and sand overlay and the other a traditional homogeneous sand dune. They found that the clay core dune survived longer and exceeded performance measures as compared to the homogeneous sand dune. In Louisiana, barrier islands have been restored with a sand beach on the Gulf side of the island and fine clay and silt on the back barrier to create a marsh. During times of overwash, the marsh serves as a platform to capture sand transported from the Gulf side of the island (Figure 6).

Figure 6. Chaland Headland, Louisiana restoration project during construction showing different types of sediment placed (looking southeast, 1 September 2006).

The rate of relative sea level rise at the project site is factored into the design of barrier island restoration projects through the long-term cross-shore transport of sediment on both the ocean and bay shorelines (Q_{oe} and Q_{be}, respectively, as shown in Figure 2). As the local mean water level increases with relative sea level rise, there is apparent erosion on the beach as the subaerial footprint of the island reduces. This erosion rate is converted to a volumetric loss that is incorporated into the long-term sediment budget for the island.

Areas with a compressible substrate composed of fine clay, silt, mud, peat, and other organics, such as in estuarine or deltaic settings, can incur a reduction in elevation and additional apparent loss of fill because of loading of the substrate by the placed sediment. Compressible substrates in the vicinity of barrier islands and coastal regions occur in Texas, Louisiana, Georgia, Virginia, and Maryland, as examples. The additional weight of the fill creates a load-induced compression of the substrate, thereby decreasing elevation of the restoration project, and must be factored into the design (Rosati et al 2006, 2007; Rosati 2009).

ENVIRONMENTAL CONSIDERATIONS:

Environmental considerations in barrier island restoration include: (1) maintaining environmental compliance during the construction process; (2) construction techniques to obtain post-project barrier island and marsh elevations as required for environmental and storm protection benefits; and (3) planting native species at the time of restoration.

Environmental compliance during construction primarily concerns reducing turbidity during the dredging and placement process. Pumping a slurry of fine sediment to the beach may require a quiescent area on the beach to allow the sediment to settle and dewater. At Chaland Headland, LA, fine sand pumped onto the beach was allowed to settle inside a dike to reduce loss of dredged sand and silt, and to minimize turbidity in the nearshore (Figure 6). Water was allowed to flow back into the Gulf at the far end of the retaining basin.

Figure 6. Dike constructed on Gulf beach at Chaland Headland, LA, to retain fine sand and silt during placement.

Fine mud pumped to the marsh side of the island was contained in a dike constructed around the perimeter of the marsh and allowed to settle 30 days to the proper elevation for native marsh species (Figure 7).

Figure 7. Dike constructed on backside of island at Chaland Headland to retain fine clay, silt, and mud during marsh construction

Sand fences are a low-cost means of keeping sand on the subaerial beach. Fences capture wind-blown sand and are particularly valuable immediately following restoration when the newly placed sediment is loose and easily mobilized, and mature vegetation has not yet been established. Khalil (2008) recommends construction of multiple rows of fences, in phases, beginning with the downwind-most location. Once that fence has captured sand, the next row of fence in an updrift location can be constructed.

Planting of native dune grasses and marsh vegetation is recommended immediately after construction has been completed. Active planting, rather than waiting for natural succession of native species, strengthens the restored island against early losses during storms, and provides a vegetative infrastructure to capture wind-blown sand transport. Habitat required for desired species is more likely to be met with active planting rather than volunteer growth.

To provide additional ecological habitat, it may be desirable to provide areas of the island that overwash occasionally. It should be accepted, however, that such a design may result in more rapid island disintegration through breaching, inlet formation, and segmentation, unless longshore sand transport is of sufficient magnitude to rapidly close any breach that forms. Alternatively, spits on the barrier termini could potentially allow overwash and unvegetated washover deposits. Figure 8 presents some of these design concepts, including restoration with a fine sediment core and marsh substrate, and sandy overlay on the ocean beach; sandy spit development to provide washover habitat; active planting of native dune and marsh vegetation; multiple rows of sand fences; and cross-shore dimensions at or exceeding critical values.

SUMMARY: This CHETN has presented design concepts for functional restoration of barrier islands. Functional restoration is an engineering and ecological design such that a barrier island can perform as a wave break, storm surge buffer, and ocean boundary for an estuary, bay, and mainland over the defined project lifetime. These concepts are meant to guide more detailed engineering and ecological analysis based on site-specific processes and regional setting. Key concepts of functional restoration are summarized below.

1. General guidelines for the critical barrier island cross-sectional dimensions of width and elevation were presented to minimize overwash, potential breaching, and subsequent breakup of the island. The critical width was defined as the smallest cross-shore dimension that minimizes net loss of sediment through overwash from the barrier island over the defined project lifetime. A sediment budget approach was presented to estimate the critical width. The critical elevation is less well-defined although it has been related to the maximum wave runup that occurs during the project storm, which would eliminate or minimize overwash and deposit of a washover fan on the backbarrier. These dimensions are related, as a lower elevation island would require greater width to capture washover sediment, whereas an island with elevation exceeding the maximum wave runup throughout the defined project life would not require a large width to capture washover sediment. Functional restoration is best related to critical cross-sectional area, which takes into account the sub-aerial barrier island area.

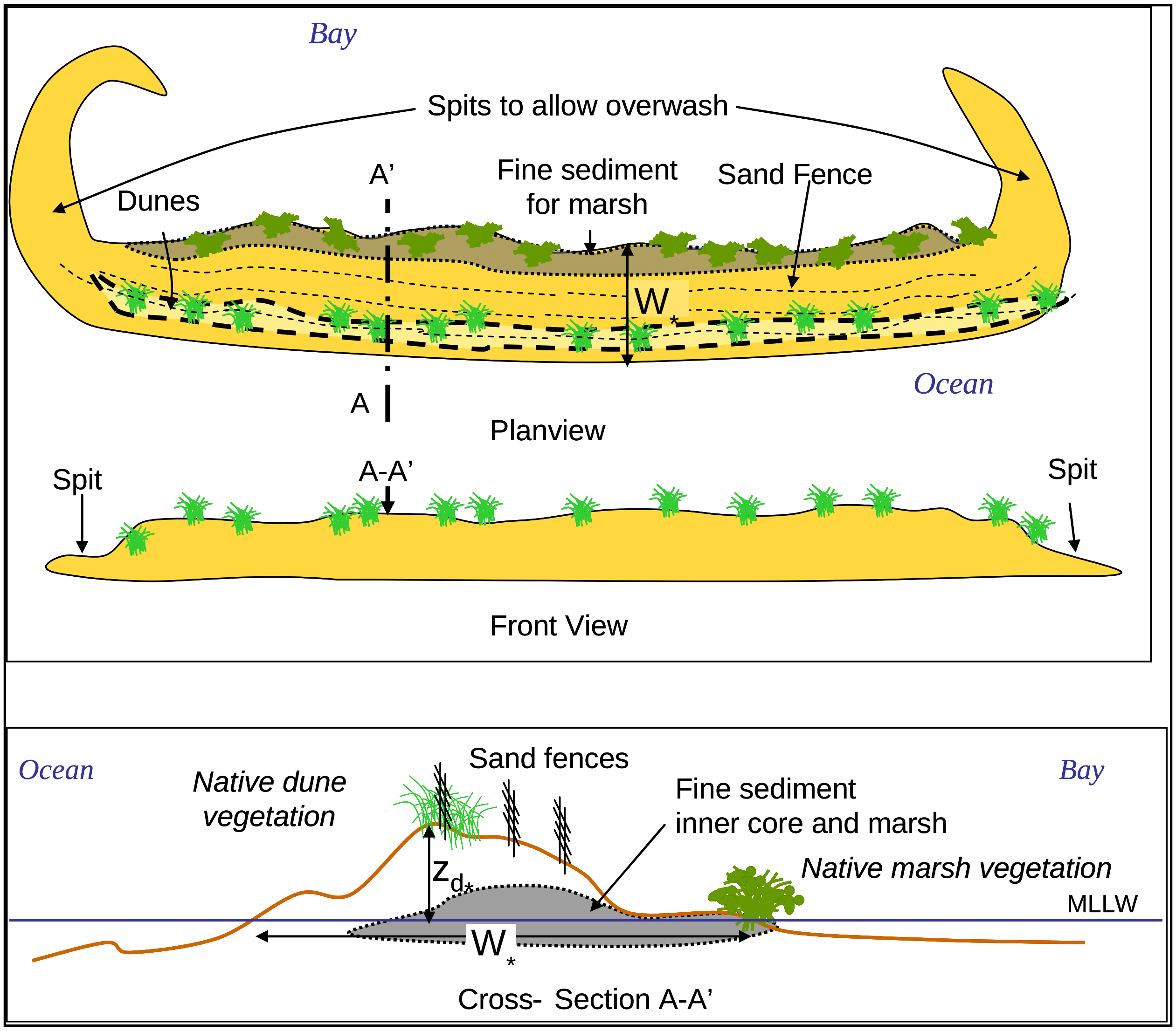


Figure 8. Conceptual design for functional restoration

2. Local sources of sand for beach restoration are diminishing along most coasts. Restoration of barrier islands using fine sediment to form the island core and a back barrier marsh platform may be a cost-effective means to achieve critical island dimensions. To minimize loss of sand placed over the core and create habitat, sequenced construction of sand fences is recommended, as well as planting with native dune and marsh vegetation.

3. Low dune elevation can promote overwash during higher water levels and formation of washover fans, desirable habitat for certain species such as the piping plover. However, to avoid breaching, inlet formation, and breakup of the island, low elevations are not recommended within the main (central) section. Spits or sacrificial island segments can be constructed or allowed to evolve on the termini of the island to provide washover habitat. Within a regional context, dredged material islands can be sited to reduce wave-induced erosion on the bayside of a restored island and provide additional habitat.

ADDITIONAL INFORMATION: This Technical Note is a product of the Internal Research and Investment Program (IRIP) and the Coastal Inlets Research Program (CIRP) of the U.S. Army Engineer Research and Development Center, Coastal and Hydraulics Laboratory. Questions about this CHETN can be directed to Dr. Julie Rosati (at 251-694-3719 or *Julie.D.Rosati@usace.army.mil*). For information about the CIRP, please contact the Program Manager, Dr. Nicholas C. Kraus at 601-634-2016 or *Nicholas.C.Kraus@usace.army.mil*. Reviews of this CHETN by Alison Sleath Grzegorzewski, Dr. Nicholas C. Kraus, Syed Khalil, and James Rosati III are gratefully acknowledged. This technical note should be cited as follows:

> Rosati, J. D. 2009. *Concepts for functional restoration of barrier islands*. Coastal and Hydraulics Laboratory Engineering Technical Note ERDC/CHL CHETN-IV-74. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://chl.erdc.usace.army.mil/chetn*

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